

Improved Switching Patterns of Inverters for Electric Drive Applications

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Abstract

Power losses of electric drives depend to a large extent on the switching frequency, currents, and supply voltage of the power semiconductor inverter. As these three parameters affect the motor torque and speed, they must be considered in the synthesis of the algorithms provided in the inverter adjustment. This paper presents the simulation and experimental study on a space vector modulation (SVM) inverter that supplies the alternating current (ac) electric drive with low switching losses. A new toolkit to explore different modulation techniques is described. Some methods of the load-dependent control over ac electric drive inverters are examined through simulation and experimentation. The benefits of the new discontinuous SVM algorithms upon the well-known control techniques are discussed.

Keywords

Inverters; Motor Drives; Space Vector Pulse Width Modulation; Switching Converters; Total Harmonic Distortion

Introduction

Nowadays, three-phase alternating current (ac) electric drives are employed in different industrial areas with a wide power range starting from few watts to several megawatts. Drive industry is very benefit from the present generation of power converters and intellectual microprocessors responsible for the implementation of control functions within short cost margins. Along with the main market share of about 80-90% simple drives with low dynamic voltage/frequency control (Novotny, 1996; Bujia, 2004; Casadei, 2007; Vodovozov, 2008), more sophisticated adjustments are needed for the drives that require high dynamic speed or torque regulation or high torque accuracy. Machine tools, robotics, electric vehicles are the examples of such kind of applications. Thus, vector control and direct torque control (DTC) have become the most important innovations in ac electric drives that opened the door for the researchers with the purpose of improvement on electric drive performance.

The best of the inverters for the ac electric drives would be devices that generate pure sinusoidal voltage and current of symmetrical phases. Unfortunately, a power electronic converter significantly distorts the waveforms. The distortion profile and level depend on the modulation principle of the converter switches. Any control method should perform some general demands like: a broad range of linear operation, a minimal number of switching to keep low switching losses in power components, a low content of higher harmonics in voltage and current, due to the productions of additional losses and noise in load, as well as elimination of low frequency harmonics to avoid motor torque pulsations.

Power losses affect efficiency, cost, weight, size, power quality, transient responses, power consumption, and other characteristics of electric drive. Consideration on the motor parameters along with the power converter development or choice inevitably leads to the power economic design and loss decreasing. In this paper, the inverter output characteristics are related to the properties of the induction motor.

Due to an influence of electromagnetic processes in the inverter-motor system, the load voltage transients have no direct relation with the reference signals. The degree of such discrepancy depends on both the motor parameters and the mode of inverter operation. Frequently, this results in additional voltage distortion and reduced usage of supply power. Therefore, the load parameters should be considered in synthesis of the switching patterns, mainly by setting the commutation law and duration of the switching intervals.

To take into account the motor voltage and current, two paths may be selected:

- using voltage and current predefined values in the procedure of switching pattern generation
- correction of the switching patterns using the

current/voltage feedback signals of the electric drive

Both methods may improve the electric drive performance (Vodovozov, 2008). The former is less expensive through less accurate. While the latter requires additional equipment but can result in higher effect.

As there is no direct relation between the mentioned motor and converter parameters, their correlation will be examined in the following sections in conjunction with the concept of load-dependent inverter control.

Firstly, the new toolkit *eModule* is described. This software opens the broad possibilities to analyze and study multiple switching patterns for the three-phase inverter-fed induction electric drives. The suitable induction motor model is used in the soft tool that takes into account motor inductances, resistances, and flux linkages while an inverter is examined and tuned. Meaning that neither simulation program can perfectly represent all parameters and aspects of real equipment, a developed experimental setup is also discussed in this section.

Next, performance simulation and experimental studies on current-dependent clamping of inverter legs demonstrate the decrease of losses and temperature in power switches and in an induction motor. A designed algorithm and implementation technique have been confirmed by simulation and experimentation study of an inverter-fed electric drive.

After that, the principle of elimination of short pulses from the switching pattern will be explained aiming to reduce the number of IGBT commutations. This method opens a way to choose the optimal switching frequency with respect to particular application performance.

Further, comparative analysis on both modulation methods will show their particular benefits and drawbacks.

Finally, an adaptive approach to the selection of optimal switching patterns is described.

A Toolkit to Optimize Switching Patterns

The aim of the developed *eModule* toolkit is to search the switching patterns, including the switching law, switching frequency, and switching pulse distribution, which provide the most power effective converter performance in the scope of the required voltage and current THD indices.

The package is enveloped into some modules, each performing different types of operations. For the best coherence, all the programs are joined by the common user interface thus providing a uniform layout and functionality. Using the front panel, a designer can interact with the software to choose the required mode of performance and to set up new ranges and parameter values in algorithms

The toolkit aims to analyze and study three-phase bridge inverters offering the solution to the following project management problems:

- informational support throughout the selection of optimal switching patterns
- mathematical and computer simulation along with full computation
- test and result verification in accordance with multiple criteria
- comparison, tuning and optimization of control systems

The toolkit involves the following components:

- a body of adjustable controller schemes
- the model of an electromagnetic and electromechanical chains of an induction motor
- a signal generator to produce the test references
- the result analyzer to calculate voltage and current rms, average, extreme, and THD values
- a graphical package for representation of the steady-state and dynamic simulated processes with automatic and manual scaling and preview facilities

The three main modulation techniques are subjected to investigation by the toolkit – six-step modulation, pulse-width modulation (PWM), and space vector modulation (SVM). In the package, the generic control method is based on the SVM approach. The list of SVM variants includes two continuous and four discontinuous patterns:

- conventional continuous SVM
- new continuous SVM with elimination of short pulses
- conventional discontinuous SVM with on-clamping
- conventional discontinuous SVM with off-clamping

- new discontinuous SVM with current-dependent clamping
- new discontinuous SVM with elimination of short pulses

PWM and six-step modulation are considered here as the descendants of the generic SVM method. Such approach simplifies an analysis and comparison of different modulation techniques from the viewpoint of voltage and current profiles, ripples, and distortion. In SVM mode of operation without the short pulses, the system provides an automatic search of optimal switching frequency.

Initial data for the switching patterns generation are as follows:

$f_c = 1$ to 15 kHz – user-defined sampling frequency

$N_c = 32$ – number of timer clocks in a sample (timer frequencies 32 to 480 kHz, timer intervals 2 to 31 μ s)

$N_{smin} = 200$ – minimum number of samples in a sector

$N_{smax} = 36000$ – maximum number of timer clocks in a period

$F = 5$ to 55 Hz – user-defined referenced output frequency to specify the motor shaft speed of rotation

$T_{min} = 18$ ms – shortest period of supply voltage obtainable at highest motor speed

$T_{max} = 200$ ms – longest period of supply voltage at lowest motor speed

$T_e = 0$ to 9 ms – user-defined electromagnetic time constant of the motor

k_{mod} – user-defined modulation index for PWM and SVM

U_d – user-defined dc bus voltage

U/F – user-defined voltage-frequency option

The average IGBT switching frequency is derived for each control method.

All the inverter switches that accomplish *eModule* are considered as ideal components without losses and voltage drop in power supply and in the load. To account the real IGBT parameters, the vendors' software must be drawn after the switching pattern generation, such as the Semikron online package *Semisel* (Pou, 2011; Boglietti, 2008), *Power Module Loss Simulator Melcosim* from Mitsubishi Electric (Bazzi, 2009; Taufik, 2011), or *The IGBT Selector Tool* from International Rectifier. Such approach allows gaining

of analysis power along with the design development suitable to explore the parameter influence on the system characteristics.

The voltage source inverter simulator makes it possible to connect each of the three motor phase coils to a positive or negative voltage of the dc link source. To calculate the instant values of the phase-to-supply neutral, phase-to-load neutral and inner phase motor voltages, the model of an inverter is applied in the toolkit. The rms value of the phase voltage for the described operation mode depends only on the dc link voltage U_d . The amplitude of the phase voltage reaches $\frac{U_d}{2}$ for the six-step modulation and SVM, and

$\frac{U_d}{\sqrt{\pi}}$ for the PWM. The inverter leg phase voltages are

obtained from (Bose, 2009; Kazmierkowski, 2002). The line-to-line voltages are related to the phase voltages as argued in (Vithayathil, 1995).

To calculate the voltage and current values in the machine windings, an electromagnetic model of the induction motor is intended. A generic electrical machine description applied in the toolkit is based on a detailed motor model given in (Krishnan, 1996). Simultaneously, the voltage and current amplitude and rms values are counted using this model.

The supply voltage of an inverter-fed induction motor has harmonics which give rise to harmonic current. As the motor torque is developed by the first harmonic of the supply voltage only, the phase voltages of an inverter-fed motor must be expressed by the Fourier series (Neacsu, 2006). To find the THD data, the apparatus of the numerical spectral analysis has been involved (Ribeiro, 2004). Using the fast Fourier transformation, the Fourier coefficients a_k and b_k of k^{th} harmonics, their amplitudes A_k and phases φ_k are derived with respect to each i^{th} pulse of the given N -pulsing converter output signals at the sampling frequency f_c :

$$a_k = \frac{2}{N} \sum_{i=0}^{N-1} y_i \cos(2\pi k f_c i dt)$$

$$b_k = \frac{2}{N} \sum_{i=0}^{N-1} y_i \sin(2\pi k f_c i dt)$$

$$y_k = \sum_{k=1}^i (a_k \cos(2\pi k f_c dt) + b_k \sin(2\pi k f_c dt))$$

$$A_k = \sqrt{a_k^2 + b_k^2}, \quad \varphi_k = -\arctan\left(\frac{b_k}{a_k}\right)$$

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} A_{(k)rms}^2}}{A_{(1)rms}} = \frac{\sqrt{A_{rms}^2 - A_{(1)rms}^2}}{A_{(1)rms}}$$

These models are used in multiple simulation procedures conducted by a designer through the user interface of the toolkit.

Full data about the chosen control method, the load, and supply are accessible from the particular panes of the toolkit main window. A researcher may fit different variants of parameters, frequencies, loads, and tunings from these pages. The main window includes:

- a diagram panel to display the gate, neutral, load phase (line-to-neutral) and line-to-line voltages and currents
- a panel Inputs to set such values as output and sampling frequencies, dc voltage, and modulation index
- a panel Controls to set the following switching patterns: six-step, PWM, continuous and discontinuous SVM including the special SVM modes as well as an electromagnetic time constant, and the drive control mode
- a panel Outputs to display rms and THD values of voltages and currents as well as the switching frequency
- a selector of the displaying time intervals – the full-period or the particular sector
- a selector of the displaying traces and instruments for their scaling
- the report generator

The toolkit can be effectively applied to drives working in open loop voltage-frequency control modes. At the same time, it is suitable for the vector and direct torque controlled drives. Using this software, the new types of modulation algorithms and systems of electric drive inverters have been developed.

To validate the new modulation patterns and test their effectiveness, an experimental setup has been manufactured (Fig. 1), which is accomplished by the two electric drives, the testing drive, and the loading one. To supply the tested induction motor, the three-phase inverter was packed using six IGBTs IRG4PH40KD with ultrafast soft recovery diodes of 1200 V, 15 A. To feed the IGBTs and the loading motor,

two programmable dc voltage sources 2TDK Lambda were applied. Gating was provided by the 2SD106AI dual scale driver core from Concept. A converter drive board is accomplished of the TMS320F2812 controller from Texas Instruments operated at working frequency 150 MHz, 64 KB on-board RAM and 128 KB on-chip flash memory, which has programmable dead time at the transient of switching. The board generated and converted three switching logic signals to six gating signals as well as supplied them the converter bridge for IGBT adjustment.



FIG. 1 ABB ACS800 EXPERIMENTAL SETUP

Current-Dependent Clamped Inverter Legs

As the power losses of the inverter-fed electric drive are proportional to the magnitude of the switching current, it would be advantageous to cancel the switching of inverter legs carrying the highest instantaneous currents. Using this idea, effective current-dependent discontinuous SVM methods have been proposed in (Kazmierkowski, 2000; Грызлов, 2002) and studied in (Vodovozov, 2007). In SVM, the optimized switching patterns predetermined offline according to either optimization criteria are stored in a memory and used in real time in the procedures of a microprocessor controller. Particularly, thanks to the preliminary current calculation, the switching patterns may be determined by counting ahead of the real current. As it is shown in (Neacsu, 2001; Neacsu, 2006), the current vector trajectory is a continuous function within a single time interval in which the voltage is kept constant. Since the voltage space vector changes its position discretely at each 60 degrees, the current space vector trajectory results are close to hexagonal for an inductive load (Fig. 2).

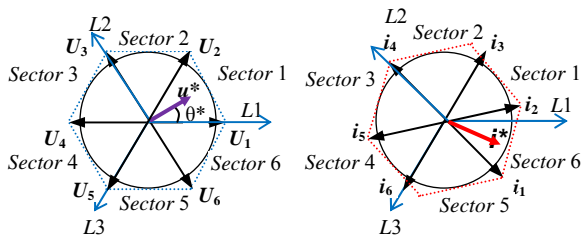


FIG. 2 VOLTAGE AND CURRENT SPACE VECTOR DIAGRAMS

Thus, the current vector position may be identified off-line and stored in a lookup table before modulation. At the beginning of every modulation sector, the control system calculates and selects from the lookup table the voltage phase, which is expected to pass the highest current. It clamps an IGBT switch of this phase by 60° alternately to the lower and upper levels of the dc voltage thus preventing the high current commutation. An example list of the locked switches counted with respect to Fig. 2 is presented in Table 1.

TABLE 1. IGBT SWITCHES WITH HIGHEST CURRENT DESTINED FOR CLAMPING

| State | Sector 1 | Sector 2 | Sector 3 | Sector 4 | Sector 5 | Sector 6 |
|---------------|----------|----------|----------|----------|----------|----------|
| Non-switching | VT1 | VT3 | VT2 | VT1 | VT3 | VT2 |

In the favorable conditions, when modulation is clamped for the phase conducting the maximal current, switching losses should decrease up to 50 % (Kazmierkowski, 2000). To implement the same algorithm, an alternative can be used by providing an online current calculation in every sector. This approach may be effectively implemented by sensing the maximal phase currents before each sector processing rather than its calculation and storage in a lookup table. By comparison of the three phase current values, the highest one is selected by the control circuit and excluded from the commutation process.

The voltage and current waveforms of the proposed current-dependent SVM acquired by simulation and experimentation are presented in Fig. 3.

Here, the states of the top switches of the three-phase bridge inverter as well as the line-to-line voltages and currents of electric drive are given. The first IGBT is clamped at sectors 1 and 4 as the corresponding current obtains its maximum. Similarly, the second leg is clamped at sectors 3 and 6, and the third one is clamped at sectors 2 and 5 as the respective current obtains their maximum. Simulation was executed for the maximal shaft rotation frequency 50 Hz,

modulation index 0.866, dc link voltage 512 V, and electromagnetic time constant 2 ms.

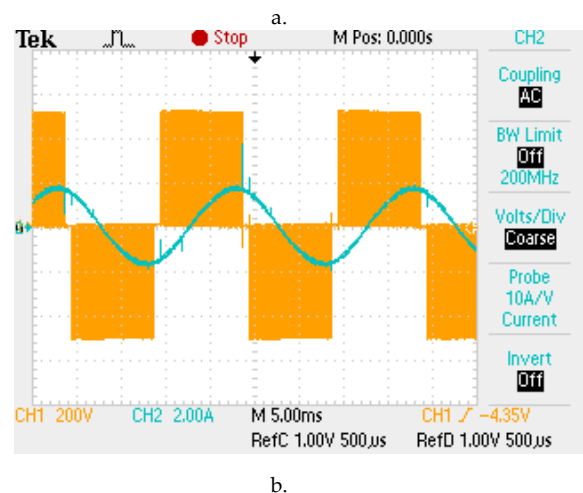
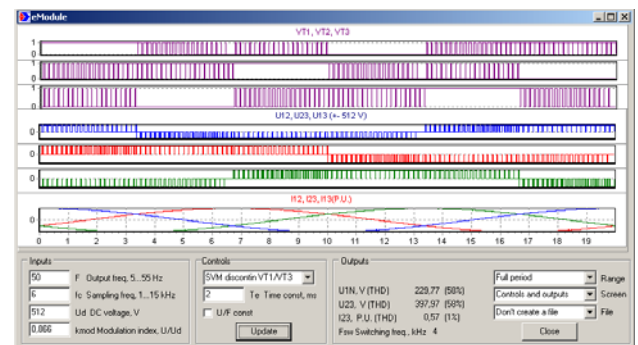


FIG. 3 WAVEFORMS OF SVM WITH CURRENT-DEPENDENT CLAMPING OBTAINED FROM EMODULE (A) AND EXPERIMENTAL SETUP (B)

Elimination of Short Pulses from Patterns

When the conduction delays of IGBT inverters become very short, there is insufficient time to reverse bias the off-going IGBT or to change the motor current which defines the speed and torque of the drive. Therefore, if the modulation scheme calls for a delay width below the minimum time, this delay should be omitted. Taking into account this consideration, both the continuous and discontinuous SVM algorithms can be accomplished in two different ways. In both cases, the control system is entrusted to an online or offline comparison of each calculated time interval with the decile of the motor electromagnetic time constant T_e .

Using the first approach, while an interval is less than $0.1 T_e$, its value is missed from the gate driver sequence and saved in the controller memory before the next sampling. Within the next sampling, this value is added to the calculated time interval and the sum is compared with T_e again. As soon as the summing time overcomes $0.1 T_e$, it is used in the commutation process.

At the second approach, while an interval is less than $0.1 T_e$, the sampling period T_c is increased and calculations repeat. As soon as all the time intervals overcome $0.1 T_e$, they are ready to be used in the commutation process.

To verify the algorithm, simulation and experimentation have been performed. Both the discovered schemes were calculated at the beginning of the sampling periods based on the value of the reference voltage vector and electromagnetic time constant. Therefore, references were updated in every sampling interval. The waveforms for the second algorithm of continuous SVM where the short pulses are eliminated are given in Fig. 4. Examination was executed for the motor running upon the maximal shaft rotation frequency 50 Hz, dc link voltage 512 V, and electromagnetic time constant 3 ms.

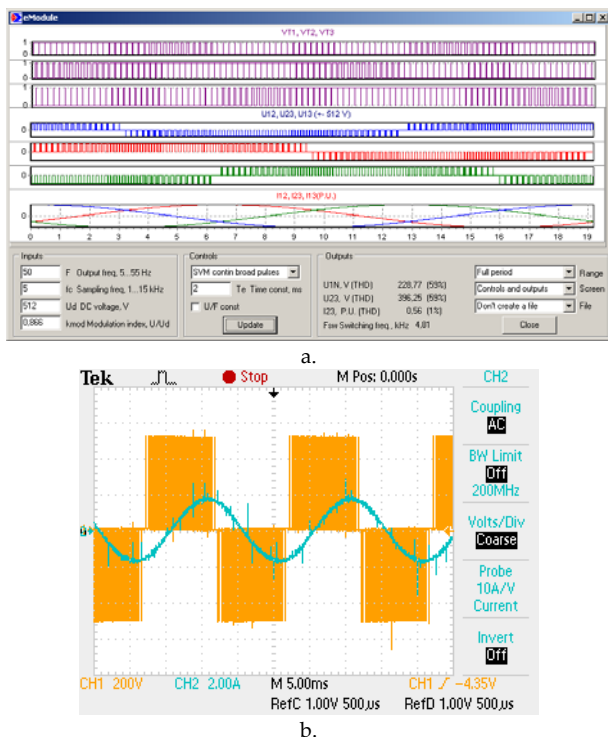


FIG. 4 WAVEFORMS OF SVM WITH ELIMINATION OF SHORT PULSES OBTAINED FROM EMODULE (A) AND EXPERIMENTAL SETUP (B)

Analysis of Load-Dependent Control

According to (Bose, 2000; Bocker, 2007; Padmavathi, 2011), the most important performance index for a power converter refers to the harmonic content in the output current. The THD comparative study on conventional and new modulation techniques was executed on the experimental setup at the rated speed motor running upon the load of 2.1 Nm. THD measurements were taken by digital oscilloscope TPS2000. In Fig. 5, the comparative data are presented for six-step

modulation, sinusoidal PWM, conventional continuous SVM with elimination of short pulses, conventional discontinuous SVM, and discontinuous current-dependent clamped SVM.

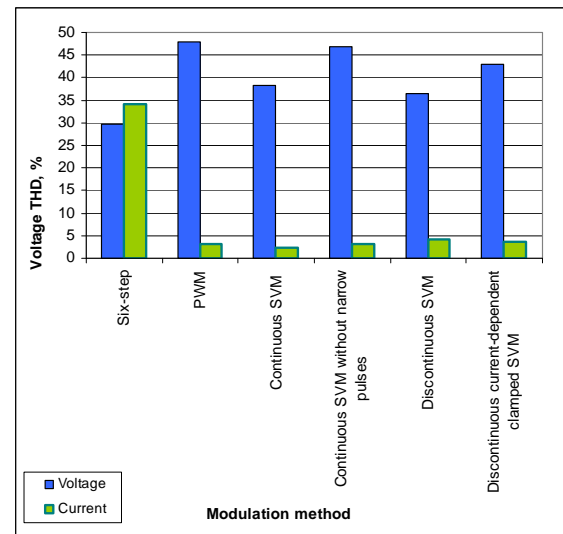


FIG. 5 THD OF MODULATION TECHNIQUES

The best harmonic content was achieved for conventional continuous SVM with high modulation index ($k_{mod} = 0.866$). Continuous SVM with elimination of short pulses (3 kHz of sampling frequency) results in almost the same THD as high-frequency PWM (6 kHz of sampling frequency) therefore it can be effectively used instead of PWM. The discontinuous SVM with current-dependent clamping develops better current THD value than the conventional discontinuous SVM. Taking into account the reduced commutation current, this method is recommended instead of the conventional one.

On the next step, to evaluate and compare the same modulation methods, the heat analysis was performed. The portable infrared thermometer from Raytek with 13 mm spot was used for IGBT and motor temperature measurements which were taken in 0.5 hours after the running. The temperature bars in Fig. 6 display the results acquired from the experimental setup.

As follows from this diagram, the six-step method causes the highest losses because of the significant current THD level and torque ripple. The IGBT losses of continuous SVM without short pulses are less than those of PWM and continuous SVM. On the other hand, the discontinuous SVM causes higher motor heating than discontinuous PWM and continuous SVM resulting in higher losses. The discontinuous current-dependent clamping SVM provides minimal losses.

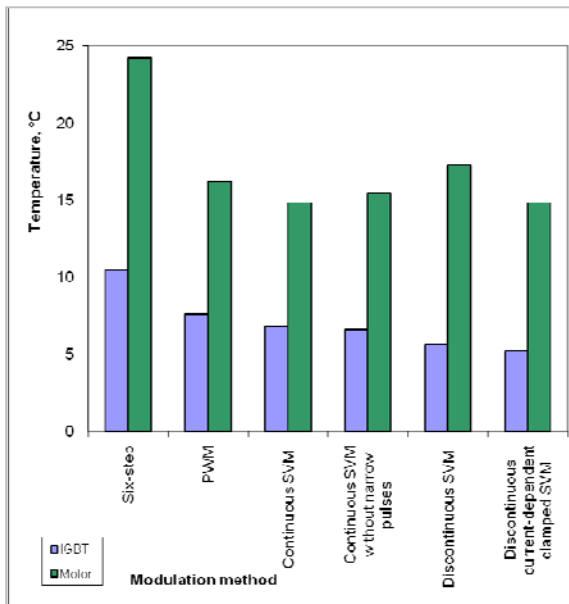


FIG. 6 IGBT AND MOTOR TEMPERATURES OF MODULATION METHODS

Finally, the motor speed and torque ripples have been analyzed. The ripple diagrams are shown in Fig. 7.

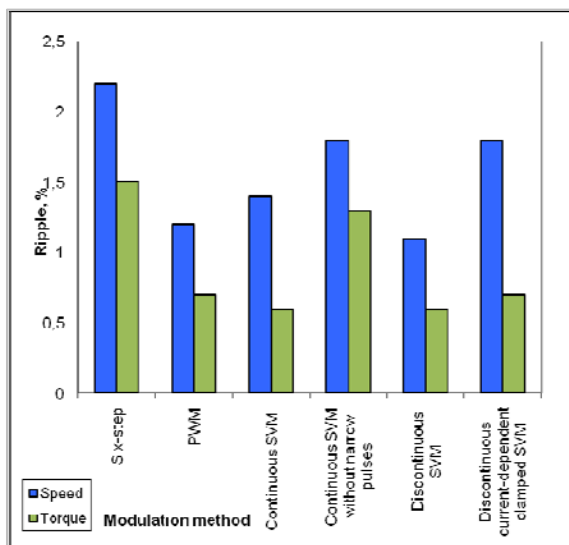


FIG. 7 SPEED AND TORQUE RIPPLES OF MODULATION METHODS

Using an oscilloscope TDS, the ripple factors ΔA were calculated as follows:

$$\Delta A = \frac{A_{pp}}{A_d} \cdot 100\%$$

where A_{pp} is an ac peak-to-peak speed or torque value and A_d is a dc particle of the same signals. The speed signal has been acquired from a tacho mounted on the motor shaft. Beforehand, the tacho ripples were measured at the grid-supplied motor. In calculation, this noise was deleted from the speed wave. To gain

the torque, the current of the loading motor was measured using the current probe Model PR30 from LEM. Again, its own noise was taken into account. The torque was found as the product of measured current and the dc motor constant. The diagram analysis confirms that all the examined methods keep the ripples within the permissible 3 % range.

An Adaptive Approach to Modulation

An adaptive approach to modulation has been discussed in (Kazmierkowski, 2002; Neacsu, 2006). The concept of adaptive SVM providing the use of the full modulation range for maximal reduction of power losses, proposes a choice of the optimal switching frequencies, currents and voltages in conjunction with the required electric drive operation.

To find the preferable modes of operation, the relation was studied between the modulation index and the switching frequency for different modulation methods of the voltage-frequency controlled electric drive with 512 VDC inverter. The goal was to find the minimal sampling frequency sufficient to keep the current THD in the 3 % range. Results of the study are shown in Fig. 8.

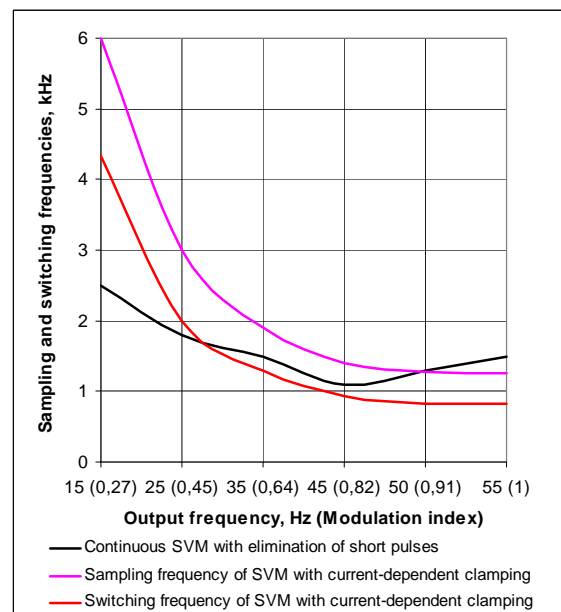


FIG. 8 SAMPLING AND SWITCHING FREQUENCIES VS. OUTPUT FREQUENCY FOR THE VOLTAGE-FREQUENCY CONTROLLED DRIVE

According to Fig. 8, two optimal modes of SVM can be recommended to achieve adaptation. These modes are shared in the range of modulation index (k_{mod}) as follows:

- $0 < k_{\text{mod}} \leq 0.5$ – continuous SVM with elimination of short pulses
- $0.5 < k_{\text{mod}} \leq 1$ – discontinuous SVM with current-dependent clamping

In contrast to (Kazmierkowski, 2002) where four adaptive regions were suggested, and (Neacsu, 2006) where six and more regions were proposed, this study indicates that the two above given methods fully meet the demands of adjustable electric drive with voltage-frequency mode of operation. Within the first region of low speeds (less than 30 Hz) and voltages (less than 300 V) the sampling frequency and switching frequencies may be reduced below 2.5 kHz of 4.5 kHz for continuous SVM. In the second region of high speeds (30 to 55 Hz) and voltages (300 to 415 V) the peak of the load current should be located in the center of the clamped sectors for maximal reduction of switching losses. In this band, either online observation of the load current or using of the precalculated motor model is required.

Conclusion

The space vector based approaches that diminish the losses and heating of the IGBT inverters have been proposed in this paper. Effective methods of the reduced switching are intended for industrial applications built on induction electric drives. Advantages of the proposed techniques are illustrated by the performance simulation in the new toolkit and experimentation on the developed physical prototype. The decline of heat as well as the reduction of conduction and switching power losses demonstrate effectiveness of the offered technology.

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